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Bilateral transfer in active and passive guidance-reproduction based bimanual tasks: effect of proprioception and handedness

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Abstract— **Recently, bilateral movement training based on robot-assisted rehabilitation systems has been attracting a lot of attention as a post-stroke motor rehabilitation protocol. Since humans generate coordinated motions based on their motor and sensory systems, investigation of the innate properties of human motor or sensory systems may provide insight into planning of effective bilateral movement training. In this study, we investigate the effects of proprioception and handedness on the movement of the contra-lateral upper limb, under both active and passive guidance conditions of the robot manipulators. Active and passive guidance-reproduction based bimanual tasks were used in this study; in these the subject is asked to hold both the right and left knobs installed at the end-effectors of two robot manipulators. The results indicate that better reproducing performance was obtained when the proprioceptive input was acquired from the active guidance condition.**

I. Introduction

With the progress of the aging society, recently, rehabilitation systems have been developed based on the application of robot technology [1]. Since most stroke or spinal cord injury patients suffer hemiplegia, many robot-assisted rehabilitation systems have been developed to support training that focuses on one side of the upper limbs with disabilities [2]. However, many daily tasks naturally require the coordinated participation of both hands. This provides a rationale for the incorporation of bilateral movements into upper limb rehabilitation protocols[3]. Although various types of bilateral movement have been proposed to improve the functioning of the hemiplegic limb, the critical training parameters that underlie the efficiency of bilateral movement have not been clarified.

For planning an appropriate rehabilitation therapy, the evaluation and measurement of motor systems or sensory systems is one of the most important processes. Although robot-assisted rehabilitation systems have clear benefits such as repeatability and availability, the efficacy of training highly depends on how accurately the patient's bodily condition is evaluated[4]. Therefore, more precise evaluation processes are needed to design robot-assisted rehabilitation systems for providing appropriate forces and movements which are adaptive to each patient. In conventional physical therapy, since the evaluation of proprioception has several distinct benefits like reliance on motor abilities and high resolution, it is considered as suitable for use in clinical method [5]. One evaluation method of proprioception consists of moving subjects' joint to a certain position and then asking the subject to either reproduce or point at the set joint position or movement [6]. For application of this kind of method for robot-assisted rehabilitation system with bilateral movement training, it is essential to investigate the relationship between left and right proprioception. Additionally, due to handedness, the two upper limbs have different abilities in both sensory and motor functions [7]. Therefore, to investigate the relationship between both upper limbs, effect of handedness also should be considered.

One type of the sensory system, proprioception is generally considered to execute the awareness of joint angle, motion and force and play an important role for the control of goal-directed movements [8]. Research suggests that muscle spindles are primary source of the proprioception, although signals arising from the joints, tendons and cutaneous receptors also contribute to the awareness of it. Since the muscle spindles are subject to central fusimotor control [9], the proprioceptive input becomes more conspicuous through active movements than passive movements [10].

The objective of this study is to investigate the effect of proprioception and handedness on the movement of the contra-lateral upper limb in both active and passive guidance conditions. Active and passive guidance-reproduction based bimanual tasks were used in this study; in these the subject is asked to grip both right and left knobs installed at the end-effectors of two robots. In the passive guidance condition, the robot guides one hand of the subject to the target based on a tracking control of the goal-directing trajectory; in the active guidance condition, the subject moves his/her hand to the target point by himself/herself. In order to evaluate the proprioceptive input acquired from the guidance based reaching motion, the subjects are asked to reproduce the symmetrical motion with respect to the motion of the contra-lateral limb. By comparison of the experimental results obtained in the left(arm)-guidance-right (arm)-reproduction task and the right-guidance-left-reproduction task in both active and passive guidance conditions, we may discover the effects of handedness.

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II. METHOD

A. Subjects

Ten healthy right-handed, 20s and male subjects with no history of orthopedic or neurological disorders participated in this experiment. All subjects were naïve to the purpose of the experiment. In order to evaluate the handedness of each subject, we used Edinburgh Handedness questionnaire .

B. Experimental apparatus

The experimental apparatus consists of two serial manipulators with 6 degrees of freedom (PA10, Mitsubishi Heavy Industries, Ltd). At each manipulator, 6-axis force/torque sensors (ATI Industrial Automation, Inc. and NITTA corporation) are attached between the robot end-effecter and the knob. The motion of the manipulators is restricted on the horizontal plane (x-y plane in Fig.1). The monitor is 1.5 meters in front of the subjects who sit on the chair. During the experiments, the subject is asked to concentrate on the monitor.

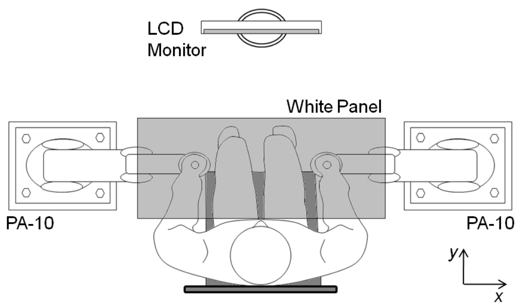

Fig. 1. Top view of experimental setup

In the active guidance condition, the positions with respect to x and y of the end-effecter are defined as the output of the second-order dynamical system described by (1).

$$F = M\ddot{z} + D\dot{z} + Kz \qquad (1)$$

The inertia (M), viscosity (D) and stiffness (K) are set to 0.1[kg], 10[N/ms] and 0.1[N/m], respectively. We choose these values based on the results of preliminary experiments, so that the subject may move the robot manipulator with sufficiently small muscle force. The values x and y are calculated based on equation (1), where z is independent variable for them. The force F is the measured force with a sampling frequency of 100Hz. In contrast, for the passive guidance condition, the robot guides one hand of the subject from the start point to the target point based on a tracking control of the goal-directing trajectory. In order to ensure the subject controls their hands based on the proprioceptive feedback through the visual information from the monitor, a white panel is placed above the knobs to prevent the subjects from viewing their hand positions. During the experiment, both the target position and the actual position of the subject's hand are recorded.

C. Target

Two knobs are 40cm apart from each other. Figure 2 illustrates an example of the task performance, where the target, start and current position of the right arm are shown in the monitor. The locations of the targets were selected by preliminary experiment to cover the primary range of hand activity, preventing extreme shoulder and elbow joint angles. To ensure reproduction of the positions of the target point based on the proprioceptive input via the contra-lateral hand movement, the target points for both upper limbs were located symmetrically with respect to the sagittal plane of the subject. A white circle is displayed for the hand position of the subject; the target and start points are displayed as black and light gray circles, respectively. In both guidance modes, when the black circle is near the target point, a straight dark gray line connecting the start point and target point is displayed to help guide the subjects in making a straight-line reaching motion. We evaluate the tracking performances of both arms to the target points.

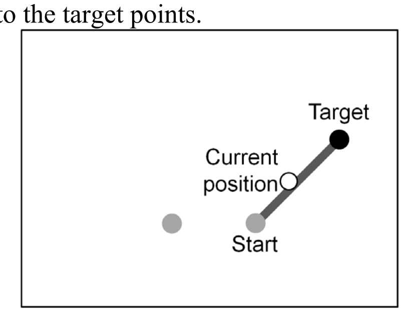

Fig. 2. Example of experimental display

D. Experimental procedure

The subjects sit on a chair that is located midway between the two manipulators and hold the left and right knobs with their left and right hands, respectively. Before starting the main experiment, the subjects have a test trial for 3 minutes to get used to the experimental environment, matching their hand movements to those of the controlled position in the monitor.

To achieve the objective of this study, the 4 experimental conditions shown in Table 1 were used to compare the subject's reproducing performances. In all conditions, the subject was asked to move one of their hands to the target point in 2 seconds (guidance mode). After stopping around the target point for 3 seconds, the robot manipulator returns the subject's hand to the start point. Since the subjects cannot see the real position of their hands directly, the subject recognizes the target position by the proprioceptive inputs of their arm. However, in conditions of C1 and C3 the robot guides one hand of the subject to the target based on a tracking control of the goal-directing trajectory, while in the conditions of C2 and C4 the subject consciously moved his hand to the target position via active movement. After returning to the start position and having a 5 second delay, in order to allow the subject time to evaluate the proprioceptive inputs acquired from the guidance based reaching movement, the subject is asked to reproduce the reaching motion with their contra-lateral hand to the symmetrically located target point (reproduction mode) in the same amount of time as the guidance mode. According to a predetermined order, the target point was shown on the monitor. Note that in the guidance mode, the subject can recognize the positions of

TABLE I

EXPERIMENT CONDITIONS

Conditions (Abbreviation)	Guidance	Reproduction	Trial number
C1(PG-LR)	Passively right	Left	15
C2(AG-LR)	Actively right	Left	15
C3(PG-RR)	Passively left	Right	15
C4(AG-RR)	Actively left	Right	15

PG and AG imply the passive and active guidance modes; and LR and RR imply the left hand and right hand reproduction modes, respectively.

both the target point and the current point of his/her hand in both active and passive conditions from the monitor. In the reproduction mode, however, the subject can recognize only the position of the target point from the monitor. Therefore, to reproduce the symmetrical reaching motion, the subjects have to refer to the proprioception input bilaterally transferred from the reaching motion in the guidance mode.

15 trials are performed in each condition. Each condition of Table 1 was performed once by each subject. In theory, iterative tasks may be affected by learning and order effects. To avoid this effect, we randomly determined the order of the experimental conditions for each subject, and had each subject take a 10 minute break between conditions in the experiment. Note that through comparison between C1 and C3(the passive guidance condition) and between C2 and C4(the active guidance condition), the effect of handedness can be investigated.

E. Measurement and Analysis

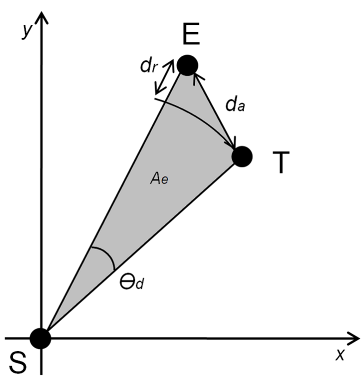

Fig. 3. Illustration of dependent variables in the case of the right arm: d_a, d_r, and θ_d represent absolute distance, range, and angular deviation, respectively. Gray area (A_e) means a measure for the deviation of the reproduction movement

The task performance was measured by how well the subject reproduced the target point that was mirror-symmetrically positioned with respect to their contra-lateral hands in the guidance mode. Figure 3 shows four variables used evaluate the reproduction performance: E, S and T are the position of the end point controlled by the subject, the position of the start point, and the position of the target point, respectively; d_a is the absolute distance between E and T; and d_r measures the range, which is the difference between the distance from the start point to the target point and the distance from start point to the position of the end point; and θ_d is the angular deviation between E and T. We also calculate the error area(A_e) as shown in Figure 3 which approximate the error, which may be defined as the integral of the difference between the target and actual trajectories.

In this study, we focus on spatial perception and do not take into consideration the temporal characteristics of the reproducing performance. A paired-samples t-test was applied to the four variables in order to detect the significant difference between active and passive guidance conditions and to investigate the effects of handedness. In order to apply the paired sample t-test to each evaluation variable, the data sets of each variable were tested for normality by use of SPSS version 16(SPSS Japan INC.).

III. EXPERIMENTAL RESULTS

All subjects completed the Edinburgh handedness inventory, which is used to assess dominance of a person's right or left hand in daily activities. The range of their laterality quotients obtained with a method reported in (Oldfield, 1971)[11], ranged from 83.3 to 100, where -100 means strongly left-handed and +100 means strongly right-handed on the scale of -100 to 100. Therefore, all subjects had strongly right-handed laterality.

In order to verify how proprioception influences the reproducing performance in the contra-lateral upper limb under active and passive guidance conditions, we measured the end-point of the upper limb performing the reproducing task, and obtained the four evaluation variables. We applied a paired-samples t-test to each evaluation variable. Table.2 shows the average values and the standard deviations of the evaluation variables for each condition of the ten subjects. In Figure 4, the results of the paired-samples t-test are summarized.

A. Comparison between the active and passive conditions

Based on the results shown in Table 2, the comparison between the active and passive guidance conditions (C1 and C2 for left hand reproduction mode and C3 and C4 for right hand reproduction mode) indicates that for both left and right hand reproduction modes, more accurate reproducing performance was obtained when the proprioceptive input was acquired from the active guidance condition (C2 and C4). Figure 4 shows the paired-samples t-test results for each variables and it indicated the significant difference between active and passive guidance conditions in the four evaluation variables.

TABLE II

EXPERIMENTAL RESULTS

Conditions	Absolute distance(mm)	Range (mm)	Angular deviation(^{0})	Error area (mm^2)
C1 (PG-LR)	71.96 (24.72)	55.58 (24.36)	-11.54 (4.57)	6183.25 (2466.15)
C2 (AG-LR)	60.55 (22.22)	46.27 (22.53)	-10.71 (4.11)	4079.51 (1639.16)
C3 (PG-RR)	34.01 (12.15)	29.48 (12.52)	-2.343 (5.43)	2111.33 (1328.40)
C4 (AG-RR)	28.41 (10.78)	23.87 (12.27)	-1.40 (3.38)	1026.87 (866.45)

Means(standard deviation) of absolute distance, range, angular deviation and error area in four conditions.

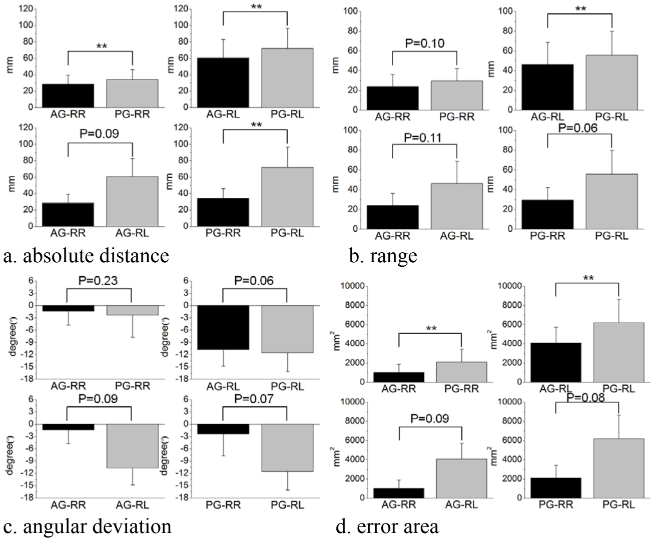

Fig. 4. Mean of ten subjects for the four variables: absolute distance, range, angular deviation and error area from a to d, respectively. The values of the paired-sample t-test are shown in the figures, where ** implies p<0.05 or the p-value is shown.

B. Comparison between the left- and right-reproduction

To investigate the effect of handedness, we also compared the results of left- and right- reproduction modes. Based on the results shown in Table 2, the comparison between the left- and right-reproduction modes (C1 and C3 in the passive guidance condition and C2 and C4 in the active guidance condition) indicate that the reproducing performance of the dominant arm was better in both active and passive guidance conditions. And the paired-sample t-test results shown in the Figure 4 show the significant difference between left-and right-reproduction mode in the four evaluation variables.

IV. Conclusion and Future work

Since evaluation of proprioception has several distinct benefits such as reliance on motor abilities and high resolution, it is confirmed that it is suitable for the use in clinical method. For application of this kind of proprioception test method for robot-assisted rehabilitation system with bilateral movement training, it is essential to investigate the relationship between left and right proprioception and effect of handedness. Because muscle spindles are subject to central fusimotor control, most of the researchers applied the passive-active testing paradigm which consists of unimanual movement task to investigate the effect of proprioception[7][9].

To investigate the effect of proprioception and handedness between both upper limbs, we extended the unimanual passive-active paradigm into a bimanual one. The active and passive guidance-reproduction based bimanual task was applied to the subject. The better reproducing performance was obtained in the active guidance condition, which is consistent with the results obtained in the unimanual task [9]. The result of this study shows that the performance differences between active and passive guidance conditions in bimanual tasks may be related to the contribution of the efferent central signals for motor command in contra-lateral upper limb. In the passive conditions, since the central signals related to the motor command were likely to be absent, the subjects were able to use only proprioceptive signals for the movement recognition.

We also investigated the effect of handedness in active and passive conditions. The experimental results showed that the reproducing performance of the dominant arm was better in both active and passive guidance conditions. Because the subjects were asked to reproduce the mirror-symmetrical motion with respect to the motion of their contra-lateral limb, handedness in sensory and motor system between dominant and non-dominant arms may result in the difference of reproducing performances. In the case of right-handed subject, the function of motor system is better brought out in left-guidance right-reproduction mode, whereas that of sensory system is better brought out in right-guidance left-reproduction mode. The experimental results obtained in this study indicate that function of motor system is more influential on the reproducing performance.

In this study, we investigated the effects of proprioception and handedness based on the spatial bimanual coupling. We did not take into consideration the temporal characteristics of the reproducing performance. Since human sensory-motor system includes both spatial and temporal characteristic, the investigation of temporal characteristic can also provide insights into the planning of the effective bilateral movement training. Additional study is necessary for the case of the temporal coupling characteristics in bimanual coordination.

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